Rogue Wave Statistics and Dynamics Using Large-Scale Direct Simulations

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LONG-TERM GOAL

The long-term goal is to study the generation mechanisms and evolution dynamics of rogue waves using large-scale three-dimensional nonlinear phase-resolved wavefield simulations and to establish the foundation for future development of effective tools for prediction of rogue wave occurrences in realistic ocean wave environments.

OBJECTIVES:

The specific scientific and technical objectives are to:

- Obtain representative large-scale rogue wave datasets using direct simulations
- Verify the validity and limitations of existing theories and models for the statistics of large-amplitude wavefields and the occurrence of rogue waves
- Understand the fundamental mechanisms for rogue wave development. Of particular interest is to validate (or invalidate) the hypotheses and assumptions underlying the existing theories, statistics and models/tools for rogue wave prediction
- Elucidate the evolution kinematics and dynamics of rogue wave events

APPROACH

The objectives stated above are achieved in a coordinated effort involving three major activities: (I) Development of a significant number of large-scale computations and datasets for nonlinear evolution of wavefields for different initial wavefield (spectral) parameters and environmental/boundary conditions; (II) Use of direct computations to quantitatively verify and validate existing theories and models for wavefield statistics and the hypotheses on rogue wave formation; and (III) Use of these computations to systematically investigate the stochastic and deterministic mechanisms underlying the

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occurrence of rogue wave events and to characterize the statistical and physical properties of such events.

For the large-scale computations, we apply the direct phase-resolved **s**imulations of **n**onlinear **o**cean **w**avefields (SNOW). SNOW resolves the phase of a large number of wave modes and accounts for their nonlinear interactions up to an arbitrary high order M including broadband non-resonant and resonant interactions up to any specified order. SNOW achieves an exponential convergence and a (near) linear computational effort with respect to the number of wave modes N and the interaction order M, and has high scalability on high-performance parallel computing platforms. Unlike phase-averaged and model-equation-based approaches, SNOW accounts for physical phase-sensitive effects in a direct way. These include the initial distribution of wave phases in the wavefield specified by wave spectrum, energy dissipation due to wave breaking, and input due to wind forcing.

From the direct simulation, we obtain datasets of wave elevation and kinematics of the complete wavefield during its evolution. By analyzing these datasets, we can determine the statistics of the wavefield, identify rogue wave events, compute the statistics of rogue waves, study the development of rogue waves and groups, and understand details of the rogue wave dynamics.

WORK COMPLETED

- Performed a significant number of SNOW computations for large-scale phase-resolved nonlinear wavefield evolution from which we obtained a collection of rogue wave data set for wavefields with different spectral parameters

- Investigated the characteristics of nonlinear wave statistics under general wave conditions based on the phase-resolved SNOW simulation datasets, and examined the validity of the existing classical theories and model equations

- Analyzed the characteristics of rogue wave statistics, the mechanisms of rogue wave event development, and the kinematics and dynamics of rogue wave events

- Developed and applied an adaptive approach to account for fully nonlinear effects of local steep waves in the phase-resolved computations of large-scale wavefield evolution

RESULTS

We found that nonlinearity affects the statistics of ocean wavefields significantly. Direct large-scale SNOW computations verify the laboratory and field observations in this context. We also found that nonlinear focusing/grouping associated with modulational instability plays an important role in the development of rogue waves. On the other hand, linear Rayleigh theory significantly under-predicts the occurrence of large (rogue) wave events compared to nonlinear wavefield simulations and field data.

***(I) Statistics of nonlinear ocean wavefields*:** By analyzing the surface wave elevation data of nonlinear wavefields obtained by SNOW simulations, we found that nonlinear wave-wave interactions impose a significant effect on the statistics of ocean surface waves. Specifically, when the nonlinear wave-wave interaction effect is included, SNOW computations qualitatively and quantitatively verified the existing field observations and laboratory experiments: (a) wave elevation distribution becomes non-Gaussian; (b) Kurtosis of nonlinear wavefields is consistently larger than that of linear wavefields; (c) nonlinear ocean wavefields exhibit frequency-dependent angular spreading with bi-modal spreading for short wave components; and (d) linear theory (Rayleigh distribution) under/over-estimates the occurrences of large crests/troughs in general. Figure 1 shows a sample comparison for the exceeding probability of wave height of a short-crested wavefield among linear theory, field observations, and nonlinear SNOW simulations. Clearly, the results in the figure indicate that (linear) Rayleigh distribution under-predicts the occurring probability of large waves with $H/H_s>2.1$. This feature, obtained from the direct SNOW simulations, agrees qualitatively well with the field observation of Mori *et al*. (2002). (In the SNOW simulation, the initial wavefield is generated from a JONSWAP spectrum and $\cos^2$-type directional spreading function with significant wave height H_s=10m, peak wave period T_p=12s, peak enhancement coefficient γ=3.3, and angular spreading width $\Theta=\pi$. The statistical results are obtained based on a Monte-Carlo simulation of 100 SNOW computations with the initial wavefields generated from the same spectrum but with different random wave-component phases. The probability distribution of wave height shown is obtained from the wavefield after a nonlinear evolution of $120T_p$.)

(II) Variation of maximum wave height during nonlinear evolution of directional ocean wavefield: Understanding of the dependence of maximum wave height on wavefield conditions is of importance to the study of rogue wave occurrence and characteristics. Based on SNOW simulations, we can obtain the time history of maximum wave height during nonlinear evolution of directional ocean wavefields. Figure 2 shows the variation of maximum wave height during nonlinear wave evolution for four different wave spectra. The four wavefields have the same peak wave period T_p = 12s and significant wave height H_s = 10m, but different enhancement coefficient γ and angular spreading width Θ: $\gamma = 3.3$, $\Theta = \pi$ for Case A; $\gamma = 3.3$, $\Theta = 4\pi/9$ for Case B; $\gamma = 5.0$, $\Theta = 2\pi/9$ for Case C; and $\gamma = 5.0$, $\Theta = 4\pi/45$ for Case D. The crest and trough are found within a directional-spreading region, specified by $[(x-x_0)^2 + (y-y_0)^2]^{1/2} < \lambda_p$ and $|y-y_0|/|x-x_0| < \tan(\Theta/2)$. The results in figure 2 clearly show that larger (rogue) waves occur in a wavefield with narrower frequency and directional spreading due to nonlinear self-focusing effect.

(III) Large wave occurrence in nonlinear wavefields of different wave spectra: In order to understand the dependence of rogue wave occurrence upon wavefield conditions, we compared the numbers of rouge wave events identified in the evolution of nonlinear wavefields (initially) specified by different wave spectra. Table 1 shows such a comparison for four different wave spectra, all of which are given by JONSWAP spectra with cosine-square angular spreading with same peak period (T_p = 12s) and significant wave height (H_s=10m) but different peak enhancement factor (γ) and angular spreading width (Θ). Wavefield size is $128\lambda_p \times 128\lambda_p$ (~30km × 30km). The rogue wave events are identified by applying large wave detection criterion at 10 sample instants (t/T_p = 60, 70, …, 150). For comparison, the prediction by linear Rayleigh theory is also shown. From the comparisons, it can be seen that linear (Rayleigh) theory under-predicts the frequency of occurrence of large (or rogue) wave events as compared to those of nonlinear wavefields. Nonlinear wave focusing and grouping rather than linear wave superposition plays an important role in the development of rogue wave events. Larger rogue waves (i.e. with higher trough-crest height) but not necessarily with higher probability are generally formed in wavefields with narrower frequency and directional spreading.

Table 1: Total number of detected large wave occurrences identified in different nonlinear wavefields. Comparison between Rayleigh theory prediction and nonlinear SNOW simulations.

	Total # of detected large wave occurrences		
Wave criterion	$\alpha=H/H_s>2.2$	$\alpha>2.3$	$\alpha>2.4$
$\gamma=3.3,\ \Theta=\pi$	52	11	2
$\gamma=3.3,\ \Theta=4\pi/9$	35	13	4
$\gamma=5.0,\ \Theta=2\pi/9$	35	17	8
$\gamma=5.0,\ \Theta=4\pi/45$	42	10	2
Prediction by Rayleigh theory	8.2	3.4	1.4

IMPACT/APPLICATIONS

Proper understanding and prediction of rogue wave events in realistic ocean environments is of critical importance to the design of surface ships and safety of naval operations and ocean explorations. The outcome of this research will establish the necessary foundation for the development of effective rogue wave prediction tools.

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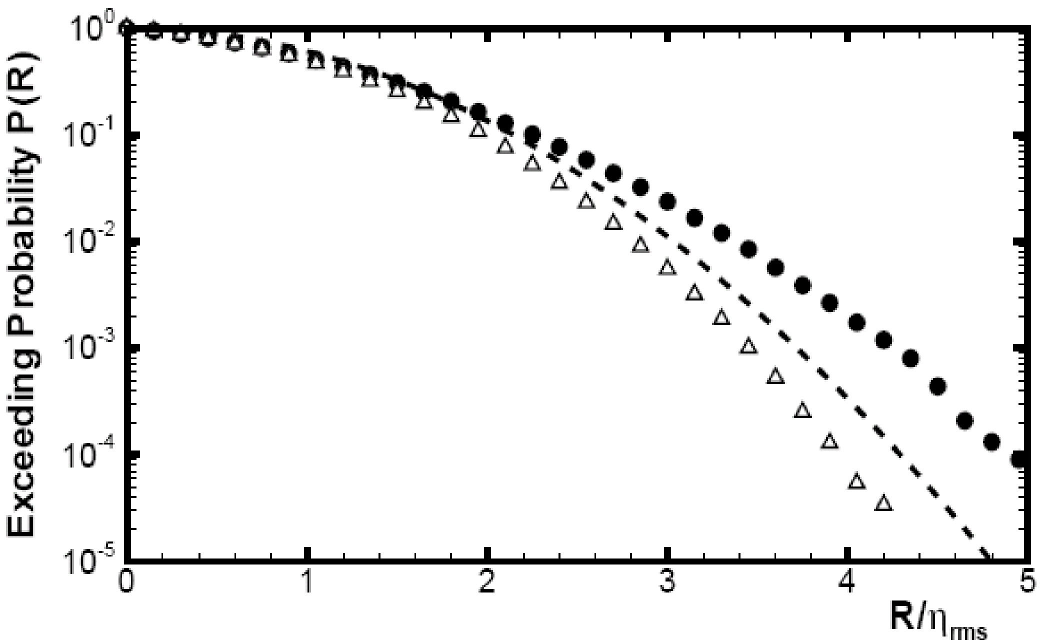
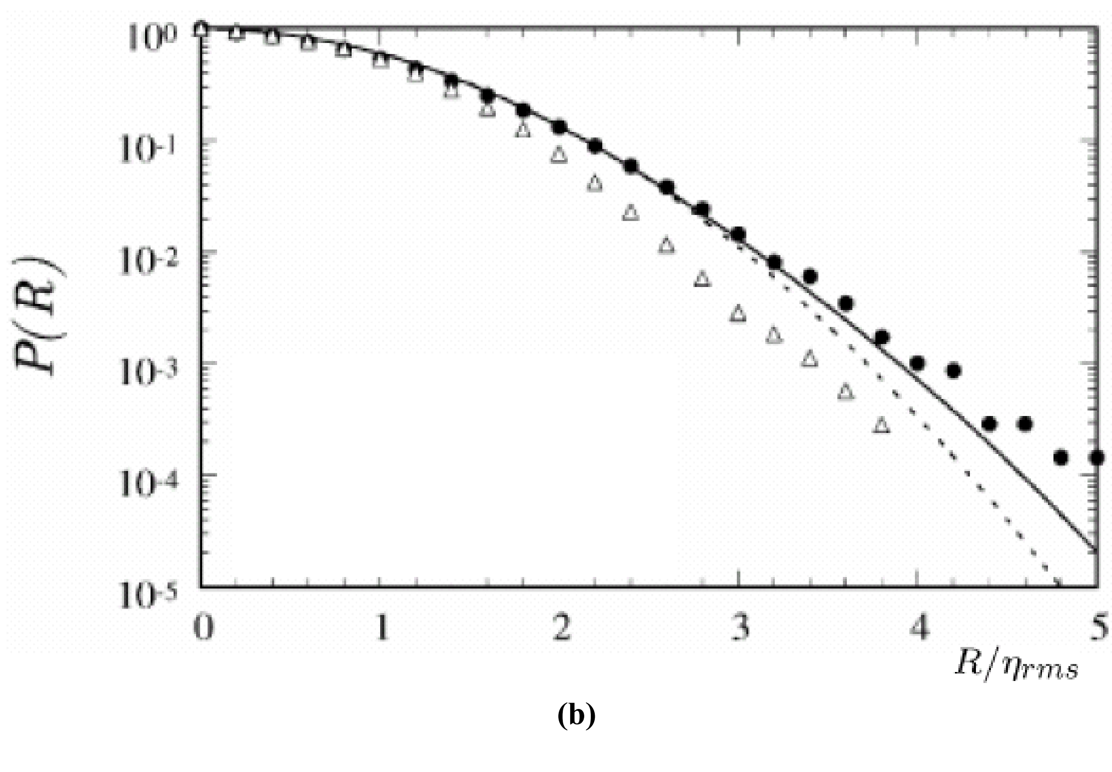


(a)



(b)

Figure 1: Comparison of exceeding probability of wave height of directional three-dimensional nonlinear ocean wavefields between (a) direct SNOW simulations and (b) field measurements of Mori et al. (2002). The plotted are: Rayleigh distribution (- - - -), crest distribution (•), trough distribution (Δ), and Edgeworth-Rayleigh distribution (——). In the figures, η_{rms}=H_s/4.

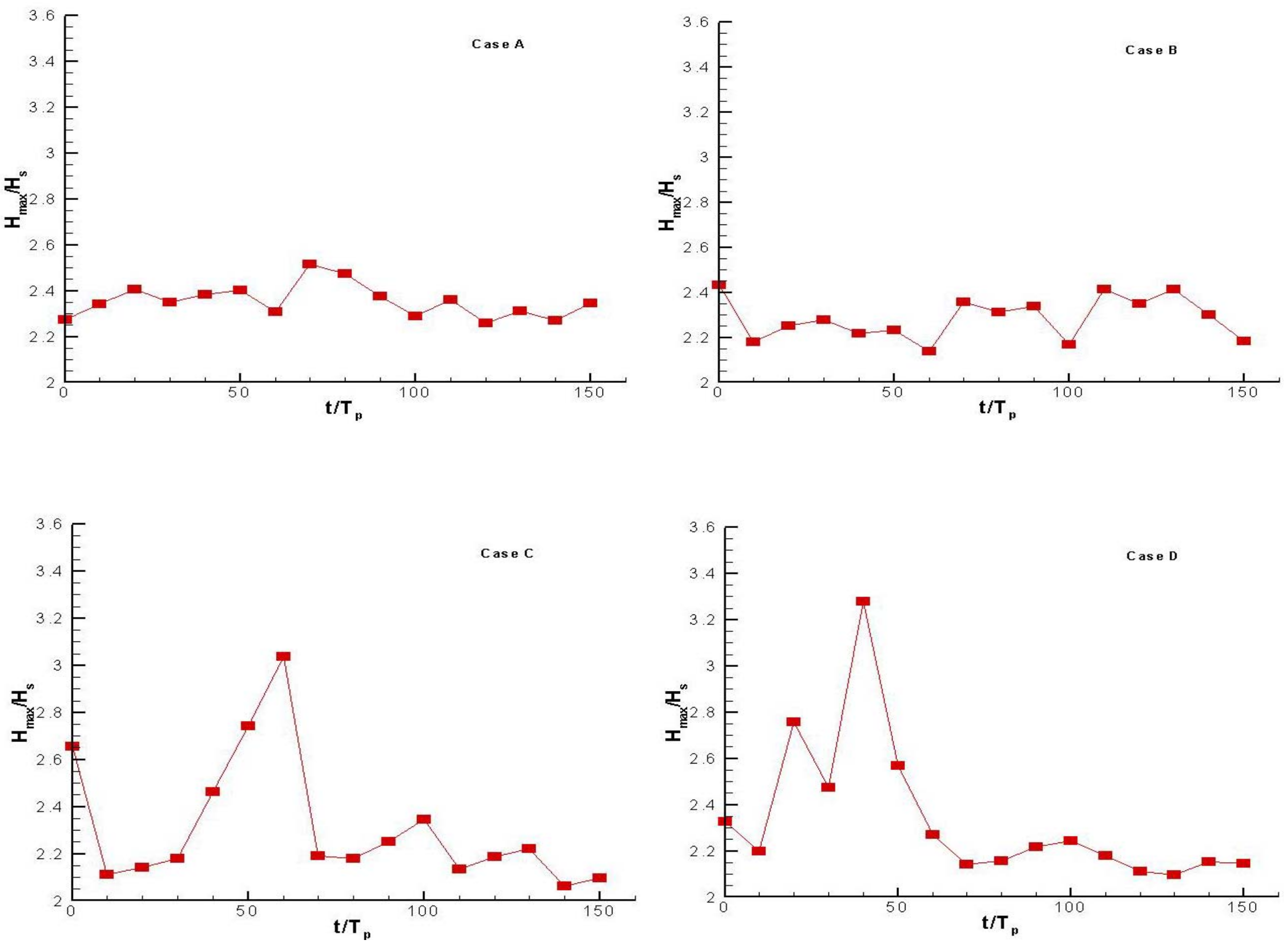


Figure 2: Variation of maximum wave height during nonlinear evolution of directional three-dimensional wavefields. The four wavefields, given by JONSWAP spectrum and cos^2-type directional spreading function, have the same peak wave period T_p = 12s and significant wave height H_s = 10m, but different enhancement coefficient γ and angular spreading width Θ: $\gamma = 3.3$, $\Theta = \pi$ for Case A; $\gamma = 3.3$, $\Theta = 4\pi/9$ for Case B; $\gamma = 5.0$, $\Theta = 2\pi/9$ for Case C; and $\gamma = 5.0$, $\Theta = 4\pi/45$ for Case D.